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**Oggier et al.**

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(54) **TIME OF FLIGHT CAMERA WITH  
RECTANGULAR FIELD OF ILLUMINATION**

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(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 547 days.

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(51) **Int. Cl.**  
**H04N 7/18** (2006.01)

(52) **U.S. Cl.**  
USPC ..... **348/135**

(58) **Field of Classification Search**  
CPC ..... H04N 7/18; G01S 17/08  
USPC ..... 348/135  
IPC ..... H04N 7/18  
See application file for complete search history.

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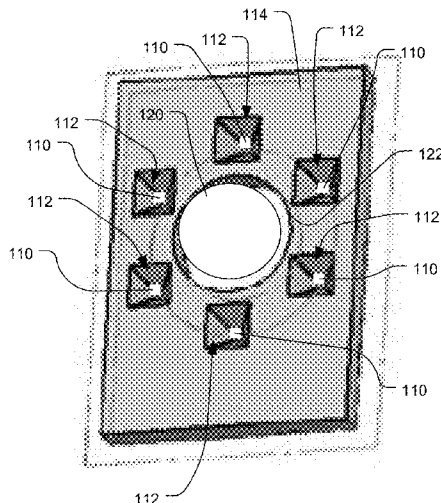
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(Continued)

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(57) **ABSTRACT**  
Improved field-of-illumination (FOI) and field-of-view (FOV) matching for 3D time-of-flight cameras is provided using light emitters with rectangular reflectors. A better adjustment of the FOI with the camera's FOV has the following advantages: optimal use of emitted light and reduced multi-path problems. Furthermore, embodiments bring the benefit for rather low-cost customization of the illumination to match the FOI to the specified FOV.

**6 Claims, 9 Drawing Sheets**



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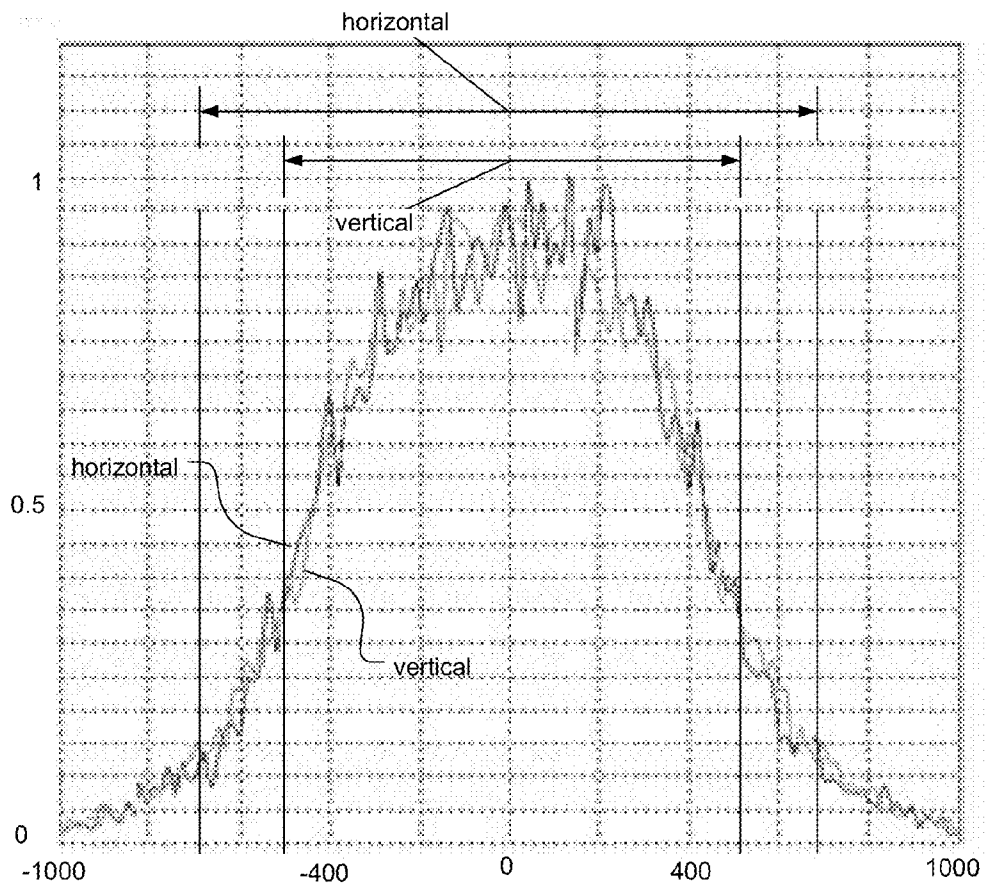


Fig. 1

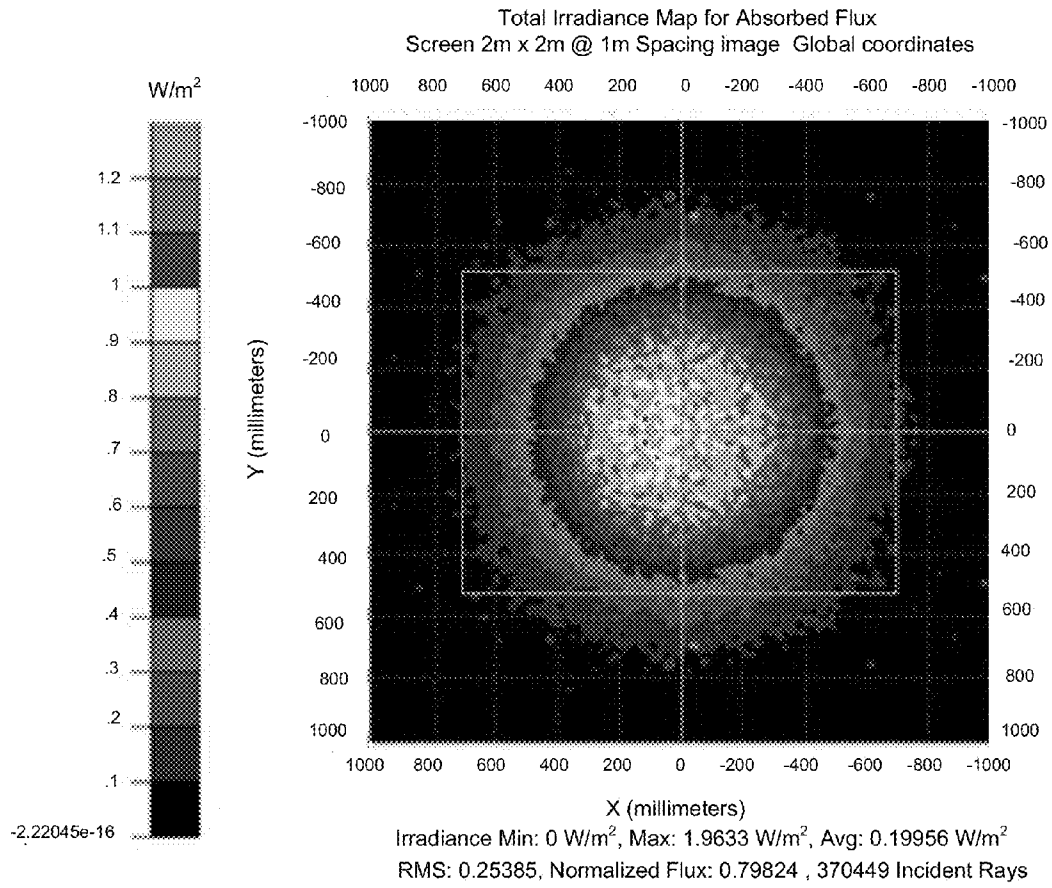


Fig. 2

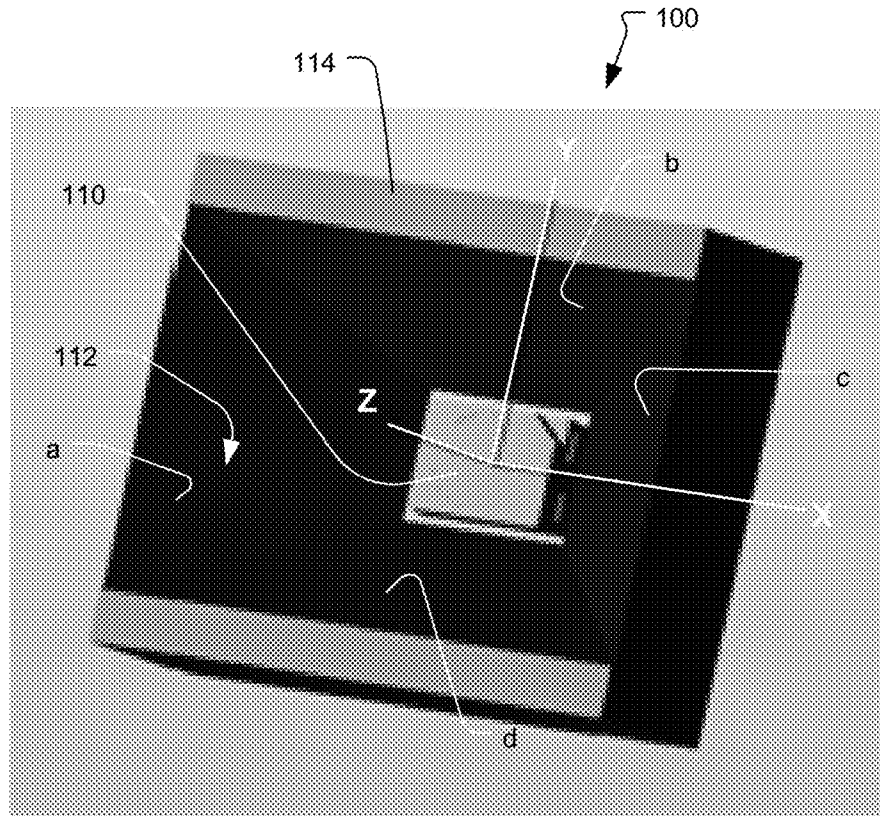


Fig. 3

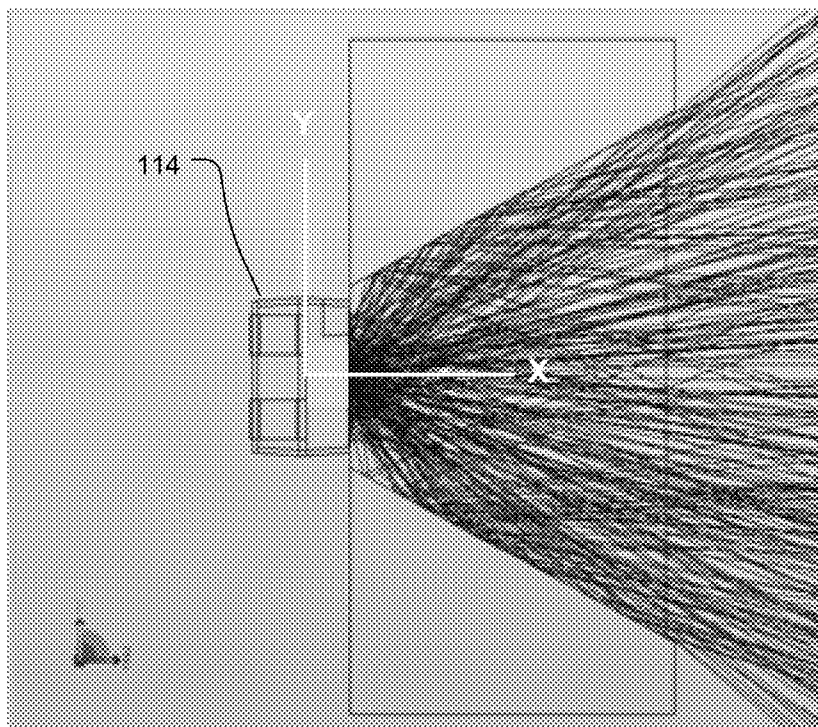
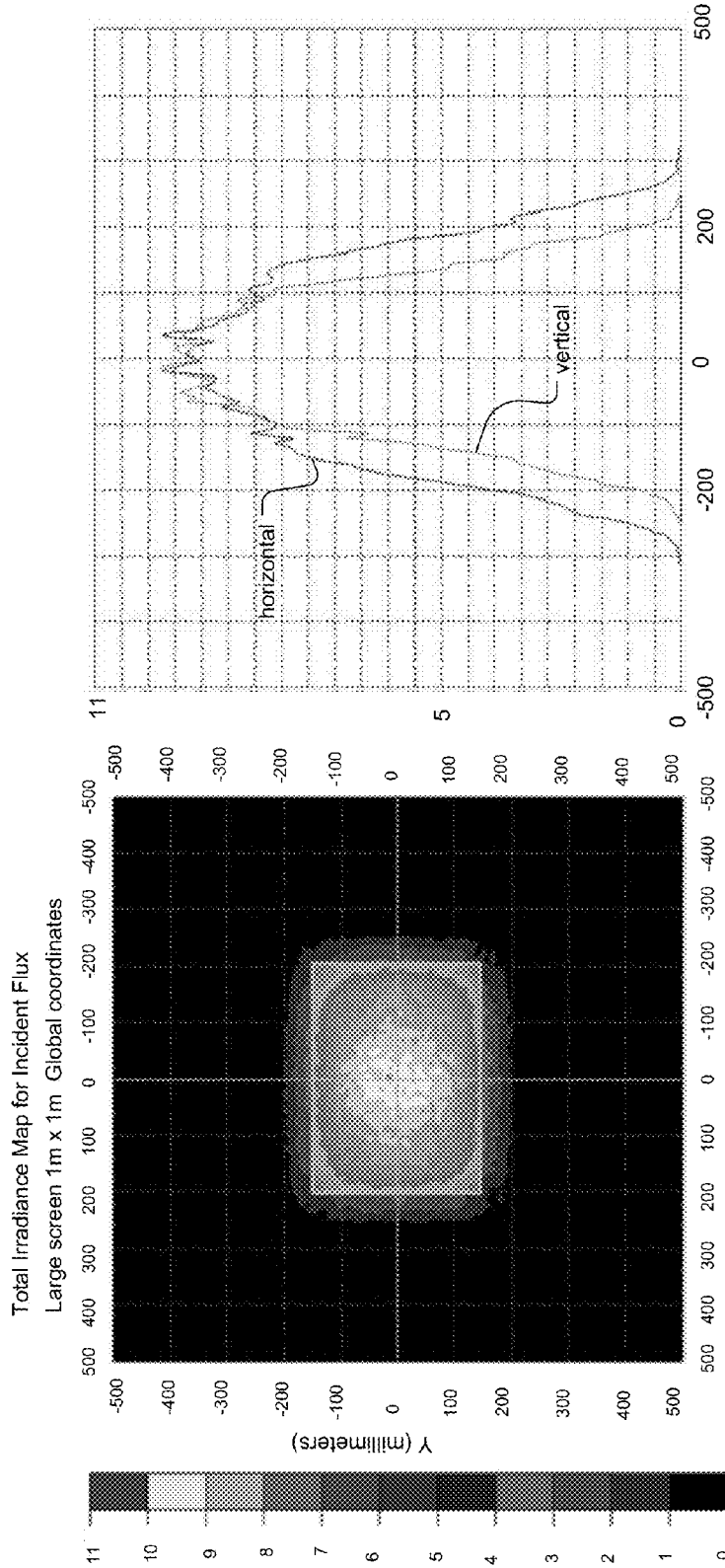


Fig. 4



Irradiance Min: 0 W/m<sup>2</sup>, Max: 10.715 W/m<sup>2</sup>, Avg: 0.91115 W/m<sup>2</sup>  
RMS: 2.1477, Total Flux: 0.91115 W, 455577 Incident Rays

Fig. 5

Fig. 6

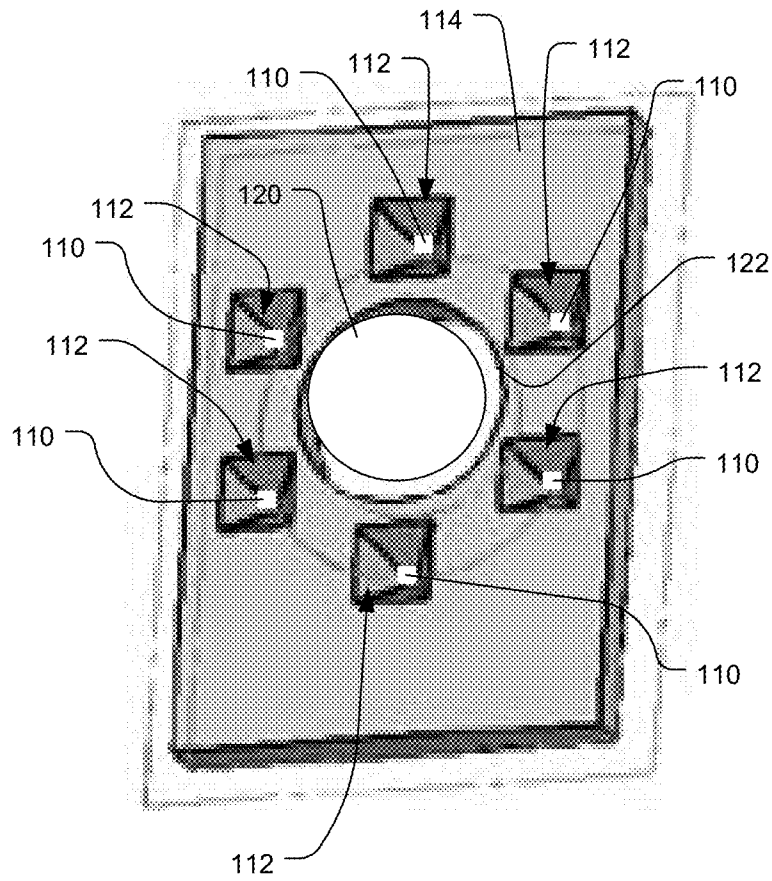


Fig. 7



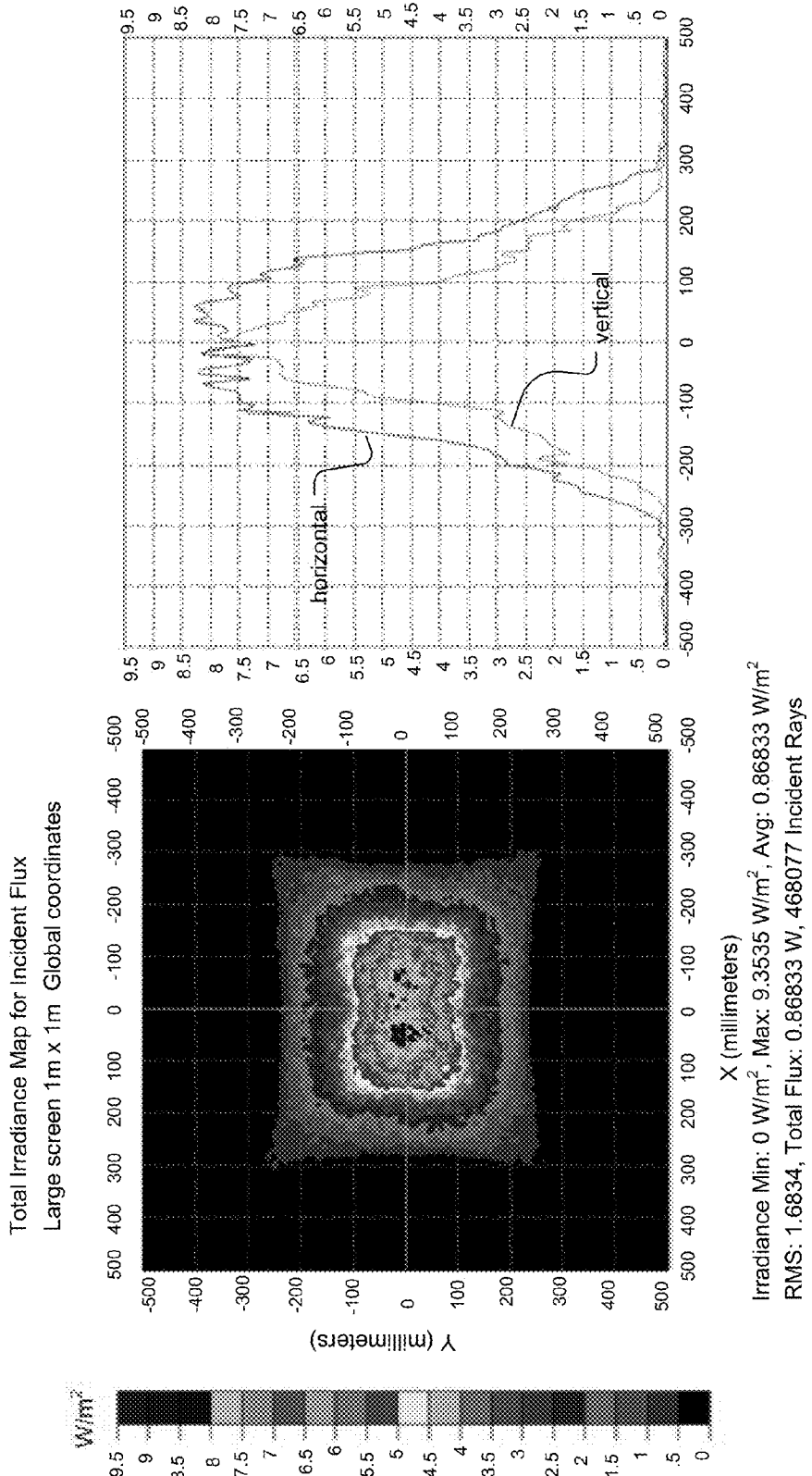


Fig. 8

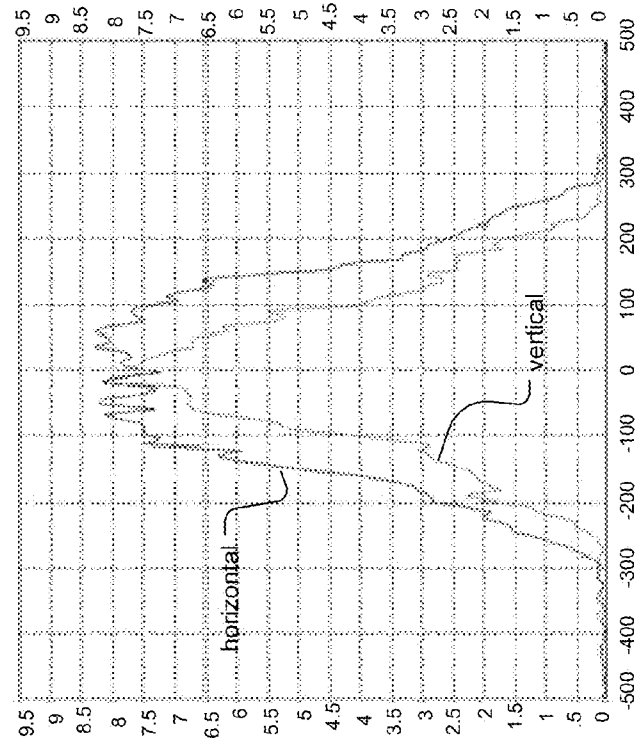


Fig. 9

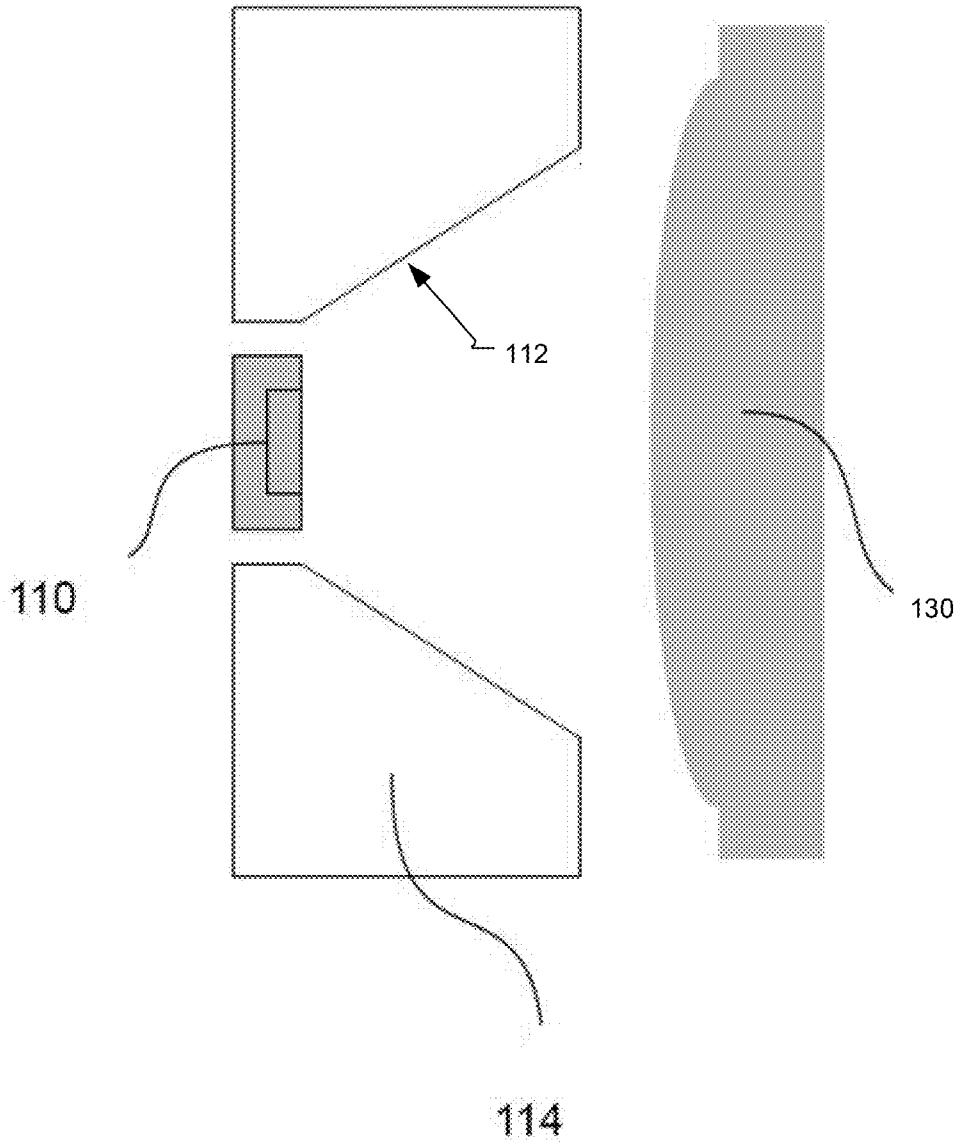


Fig. 10

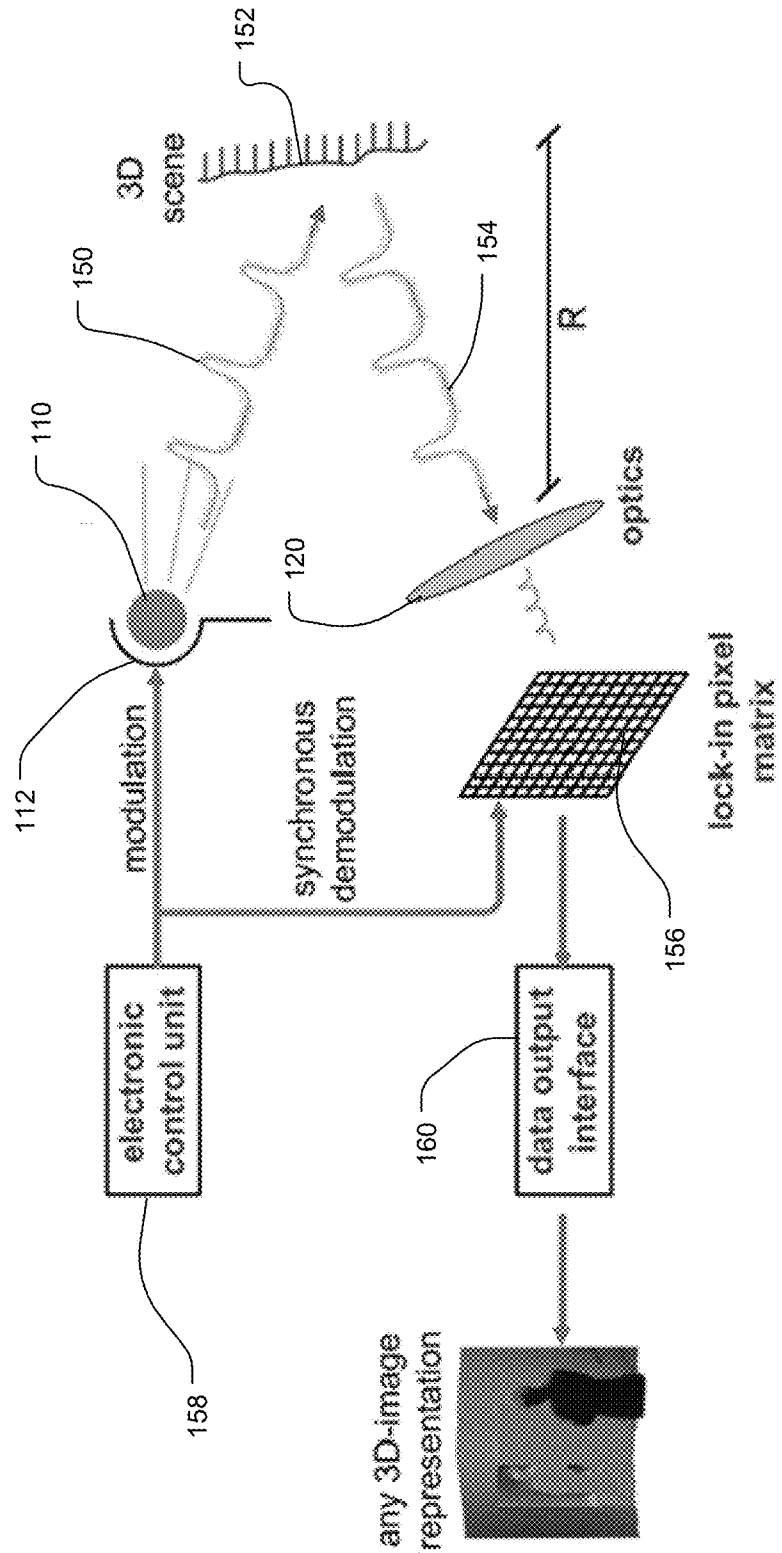


Fig. 11

## TIME OF FLIGHT CAMERA WITH RECTANGULAR FIELD OF ILLUMINATION

### RELATED APPLICATIONS

This application claims the benefit under 35 USC 119(e) of U.S. Provisional Application No. 61/230,239, filed on Jul. 31, 2009, which is incorporated herein by reference in its entirety.

### BACKGROUND OF THE INVENTION

Current commercially available three-dimensional (3D) time of flight (TOF) cameras use in general an array of light emitting diodes (LEDs) with micro-lenses that more or less have a similar field of illumination (FOI) as the field of view (FOV) covered by the camera. Laser-based 3D TOF cameras also require a specific micro-optical design to generate a FOI that matches to the FOV of the camera.

LEDs are commercially available as surface-mount devices. They can be ordered either without any micro-lens or with micro-lens. A micro-lens is required for narrower emission angles. With respect of 3D sensing, such devices have two main drawbacks:

In general, the emission field has circular shape. On the other side, the imaged area on the image sensor, which determines together with the lens the FOV, corresponds to a rectangular-shaped area, or a square-like area distorted by the lens to form a barrel, pincushion distortion. The commercial availability of different emission angles is limited. In order to get a good match of FOI and FOV, expensive custom-made light source micro-optics have to be developed.

A typical FOI pattern is shown in the simulation in FIGS. 1 and 2. They show the intensity distribution on a 2×2 m (meter) target at a distance of 1 m from the LED light source. The two pairs of lines indicate the FOV of this specific camera in the horizontal and vertical directions in FIG. 1. In FIG. 2, the rectangle shows the FOV. Especially in the corners, FOV is not well illuminated while illumination power is wasted above and below the FOV.

Narrow FOI has the advantage that most of the emitted light gets onto the FOV. However, the uniformity over the area gets lost. Usually, the light power in the center of the FOV is larger than the power at the corners. On the other side, a wide FOI shows an improved uniformity over the entire FOV, but a lot of power is wasted outside the FOV.

Other problems can arise when the FOI is wider than a FOV. It might happen that objects outside the FOV reflect modulated light onto objects in the FOV. In such a case, the receiver gets a resulting image from the direct path and the indirect path. Not only does this potentially disturb the actual range measurement of the object in the FOV, it also cannot be detected because the reflecting object is outside the FOV and cannot be seen by the camera.

### SUMMARY OF THE INVENTION

Because the commercial availability of different emission angles is limited and in most cases they do not fit the specifications of the camera's FOV, one has to start designing customized optics for the illumination. However, customizing a micro-optical design is costly and in most cases not practical in an economical sense. For that reason, most 3D camera manufacturer use non-optimized micro-optics on the light sources.

The invention proposes the implementation of a light source in combination with a reflector. The reflector is

designed such that light is deflected in a way that the FOI best covers the camera's FOV. The reflector preferably has rectangular-like shape, since the FOV in general is rectangular-shaped due to the rectangular image sensor.

In general, according to one aspect, the invention features, a time of flight camera, comprising: a time of flight detector chip for detecting light from a scene, a light emitter for producing modulated light for illuminating the scene, and a frusto pyramidal reflector for directing light from the light emitter onto the scene.

In embodiments, the light emitter is a light emitting diode or a laser diode. The frusto pyramidal reflector is metal coated and has a rectangular or square cross-section. Usually, the frusto pyramidal reflector is formed in the front cover.

The above and other features of the invention including various novel details of construction and combinations of parts, and other advantages, will now be more particularly described with reference to the accompanying drawings and pointed out in the claims. It will be understood that the particular method and device embodying the invention are shown by way of illustration and not as a limitation of the invention. The principles and features of this invention may be employed in various and numerous embodiments without departing from the scope of the invention.

### BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawings, reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale; emphasis has instead been placed upon illustrating the principles of the invention. Of the drawings:

FIG. 1 is a plot of irradiance (W/sq meter) as a function of position in millimeters for a standard LED source;

FIG. 2 is an irradiance map in millimeters showing the field of illumination relative to the field of view;

FIG. 3 is a perspective view of a light source according to the present invention;

FIG. 4 is a Monte Carlo simulation of the light emitted from the light source;

FIG. 5 is an irradiance map in millimeters showing the field of illumination relative to the field of view for the inventive light source;

FIG. 6 is a plot of irradiance (W/sq meter) as a function of position in millimeters for the inventive LED source;

FIG. 7 shows a time of flight camera with the inventive light sources;

FIG. 8 is an irradiance map in millimeters showing the field of illumination relative to the field of view for another embodiment of the inventive light source;

FIG. 9 is a plot of irradiance (W/sq meter) as a function of position in millimeters for the embodiment of the LED source;

FIG. 10 shows an embodiment based on the invention with an additional optical element set on top.

FIG. 11 is a schematic illustration showing the operation of a TOF camera.

### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 3 shows a light source **100** for a TOF camera according to the principles of the present invention.

A light emitter **110** is positioned in a rectangular reflector **112** that is formed in a frame **114**.

In the current embodiment, the light emitter **110** is an LED or laser diode. The reflector **112** comprises four angled trian-

gular surfaces a, b, c, d of the substrate **114** that angle in obliquely toward the light emitter **110** to form a frusto pyramidal cut-out in the substrate **114**. In this embodiment, the reflector **112** has a rectangular cross section. In the preferred embodiment, the surfaces a, b, c, d of the frusto pyramidal reflector **112** are coated to be reflective such as with a metal coating to direct light from the light emitter onto a scene of interest.

FIG. **4** is cross section of a ray tracing using the example of an LED light emitter **110** with the square-shaped reflector **112** formed in the substrate **114**.

FIGS. **5** and **6** show a simulation of the far field intensity pattern for an LED light source. The rectangle in FIG. **5** shows the FOV.

In addition to the above-mentioned benefits, the preferred embodiment provides higher flexibility in adapting the FOI to different applications/specifications. Specially designed micro lenses are not required. Instead, only the angles of the frusto pyramidal reflector **112** need to be adapted to the FOV.

FIG. **7** shows a 3D TOF camera. The substrate **114** that forms the front cover of the camera and comprises **6** frusto pyramidal reflectors **112** formed in the surface of the substrate **114**. In this embodiment, the reflectors **112** have a square cross section. At the bottom of each reflector **112**, a light emitter **110** is located. A center port **112** is formed in the substrate **114**. The front aperture **120** is located in the port **122** to collect light returning from the scene of interest and focus the light onto a TOF detector chip.

In later designs, the FOI can easily be modified by simply replacing the reflector plate substrate **114** with one having different reflectors. The reflector surfaces are preferably metal coated to be mirror-like.

FIGS. **8** and **9** show a simulation of the far field intensity pattern for an LED light source showing a pincushion projection of the emitted light using a reflector-type. This design of a reflector takes into account the distorted FOV of the camera.

FIG. **10** illustrates another possible embodiment of using the same reflector approach as illustrated in Figs. **3** and **4** but adding another optical element, lens, **130** that further adjusts the FOI to the requirements.

FIG. **11** shows the typical application of a 3D TOF camera. For these cameras, LED-type light emitters as light sources are disclosed in T. Oggier et al., "An all solid-state optical range camera for 3D real-time imaging with sub-centimeter resolution (SwissRanger™)", Proc. SPIE Vol. 5249 No. 65, 2003 and T. Oggier et al., "SwissRanger SR3000 and first experiences based on miniaturized 3D-TOF Cameras", 1st range imaging research day, Eidgenössische Technische Hochschule Zurich, 2005 or laser diodes light emitters as disclosed in Acharya et al. "System Design of Time-of-Flight Range Camera for Car Park Assist and Backup Application", CVPR workshop, 2008.

In more detail, the light emitter **110** produces modulated light **150** that is directed at the 3-D scene **152** by the rectangular frusto pyramidal reflector **112**. The returning light **154** from the scene **152** is collected by the camera lens **120**, which includes a bandpass filter so that only light at the wavelength emitted by the light emitter **110** is transmitted. An image is formed on the TOF detector chip **156** which is a two dimen-

sional array of pixels. Control electronics **158** coordinate the modulation of the light emitter **110** with the sampling of the TOF detector chip **156**. This results in synchronous demodulation. A data output interface **160** is then able to reconstruct the 3-D image representation using the samples generated by the chip **156** such that a range to the scene is produced for each of the pixels of the chip **156**.

Laser diodes have the advantage of possibly higher optical power per device, while LEDs are commercially available in surface mount technology and, in most cases, can be ordered with micro-lenses on top to for a given emission angle.

The invention presented herein gives the following advantages:

It renders a better matching of the field of illumination (FOI) of the light source and the field of view (FOV) of the lens/camera.

The complexity and cost to change the FOI of an existing design is significantly reduced.

Undetectable multi-path artifacts from objects outside the FOV are reduced.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.

What is claimed is:

**1.** A time of flight camera, comprising:

a substrate, forming a front cover of the camera;

rectangular frusto pyramidal reflectors formed in a surface of the substrate, wherein each rectangular frusto pyramidal reflector formed in the surface of the substrate includes a center port;

a light emitter located at a bottom of each frusto pyramidal reflector in the center port for producing modulated light for illuminating a scene;

a time of flight detector chip for detecting light from the scene; and

an aperture located in a port for collecting light from the scene and focusing the light onto the detector chip,

wherein the frusto pyramidal reflector uniformly directs the modulated light from the light emitter onto the scene so that a rectangular field of illumination matches a rectangular field of view, and light power at each corner of the field of view is equivalent to light power at a center of the field of view.

**2.** The camera as claimed in claim **1**, wherein the light emitter is a light emitting diode.

**3.** The camera as claimed in claim **1**, wherein the light emitter is a laser diode.

**4.** The camera as claimed in claim **1**, wherein the frusto pyramidal reflector is metal coated.

**5.** The camera as claimed in claim **1**, wherein the time of flight detector chip includes an array of pixels that demodulate light returning from the scene synchronously with the modulation of the light emitter.

**6.** The camera as claimed in claim **1**, further comprising optical elements to further shape the field of illumination.

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UNITED STATES PATENT AND TRADEMARK OFFICE  
**CERTIFICATE OF CORRECTION**

PATENT NO. : 8,803,967 B2  
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INVENTOR(S) : Oggier et al.

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

On the Title Page:

The first or sole Notice should read --

Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b)  
by 660 days.

Signed and Sealed this  
Sixth Day of October, 2015



Michelle K. Lee  
*Director of the United States Patent and Trademark Office*